APPLICATION

of

KRIS KELKAR

for

UNITED STATES LETTERS PATENT

on

ADAPTIVE BEAMFORMING METHODS AND SYSTEMS
THAT ENHANCE PERFORMANCE AND REDUCE COMPUTATIONS

DOCKET NO. 147-25-058

ASSIGNED TO

CALIFORNIA AMPLIFIER, INC.

ADAPTIVE BEAMFORMING METHODS AND SYSTEMS THAT ENHANCE PERFORMANCE AND REDUCE COMPUTATIONS

CROSS REFERENCES TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application Serial No. 60/446,947 filed February 11, 2003.

BACKGROUND OF THE INVENTION

Field of the invention

The present invention relates generally to wireless communication systems and, more particularly, to adaptive beamforming in such systems.

Description of the Related Art

A variety of wireless communication systems have utilized adaptive beamforming antenna methods that multiply signals received from a plurality of antenna elements (e.g., an antenna array) with complex weights and then sum the resulting products to generate an estimate of the transmitted signal. A cost function is typically based on the difference between this signal estimate and a desired signal wherein a portion of the desired signal (e.g. preamble, midamble or pilot tones) is known. An optimum set of complex weights is a set that minimizes the cost function.

Although this beamforming approach provides an optimal solution for signals received at a selected time-of-arrival, these may not be the signals of interest. For example, multipath signals (signals that travel over multiple different paths because of reflections from intervening objects) may arrive at spaced antennas at substantially-different times. Accordingly, this approach will process multipath signals that arrive at the selected time-of-arrival but spatially reject those that do not. The resultant estimate of the transmitted signal is then in error because it ignores relevant signal energy that arrived at

times other than the selected time-of-arrival.

This approach also requires the substantial computational task of solving a series of equations that will optimize N complex weights which correspond to N antenna elements. In particular, this calculation includes the inversion of an NxN matrix and the multiplication of the inverted NxN matrix by an Nx1 vector for each selected time-of-arrival.

Conventional adaptive beamforming approaches face additional problems when a system's multipath delays exceed the toleration capability of the signal's modulation format. Typically, time domain or frequency domain equalization has been used to resolve these multipath delays. In systems that incorporate adaptive beamforming antennas, however, it is difficult to integrate such equalizers with the beamforming algorithms.

Implementing the equalization prior to beamforming robs the equalization process of the beamforming gains, thereby causing inaccurate equalization. Adding the equalization after beamforming is problematic because the beamforming will treat signals with excess multipath delay as interference and therefore attempt to reject them. This reduces gains (e.g. diversity gain) that would normally enhance the desired signal via the beamforming process.

Attempts to solve these problems have generally required the initial calculation of the time-of-arrival for each multipath component that is to be constructively combined and subsequent reoptimization of the complex weights for each path. This, however, leads to substantially increased computational requirements because the required computations are multiplied by the number of paths to be processed.

Other conventional attempts have iteratively optimized the set of weights applied to each antenna element over a plurality of received symbols in order to thereby minimize the processing power required. Unfortunately, this generally increases the convergence time of the optimization so that the resulting processing gains are substantially less in the early portion of the received signal. This approach is thus particularly problematic for burst communication systems.

BRIEF SUMMARY OF THE INVENTION

The present invention is directed to beamforming concepts which include a) progressive beamforming that substantially reduces computational complexity, b) current and delayed versions of data-carrying signals that facilitate optimization of spatial information, and c) time-of-arrival information that facilitates a single matrix inversion which substantially reduces the complexity of conventional beamforming computations.

The novel features of the invention are set forth with particularity in the appended claims. The invention will be best understood from the following description when read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a wireless communication system of the present invention that facilitates a progressive beamforming method of the invention;

FIGS. 2A and 2B are block diagrams of wireless communication systems system that enhance beamforming performance with multipath signals; and

FIG. 3 is a block diagram of a wireless communication system that reduces beamforming computations.

DETAILED DESCRIPTION OF THE INVENTION

Attention is initially directed to FIG. 1 which illustrates a wireless communication system embodiment 20 that includes an array 22 of antennas 23, a radio-frequency (RF) frequency converter 24, a preprocessor 26, a beamformer 28 and a modulator/demodulator (modem) 30. The RF converter is coupled to the antenna array 22 and the preprocessor 26 couples the RF converter to the beamformer 28. The modem 30 is coupled between the beamformer and a system data port 31.

In at least one embodiment of the invention, the antenna array 22 is partitioned into subarrays 32, the RF converter 24 is partitioned into frequency converters 34, the preprocessor 26 is partitioned into preprocessors 36 and the beamformer 28 is partitioned into subarray

5   beamformers 38 and an array beamformer 39. With reference to these element partitions, each frequency converter 34 is coupled to a respective subarray 32 of antennas 23 and each of the preprocessors 36 is coupled between a respective frequency converter and a respective subarray beamformer 38. Finally, the array beamformer 39

10   couples the subarray beamformers 38 to the modem 30.

The present invention recognizes that the computational complexity for beamforming is roughly proportional to the cube of the number of antenna elements (e.g., the computational complexity of inverting a corresponding matrix increases proportionally to the cube

15   of the number of elements in either dimension of the matrix).

Accordingly, the invention provides the wireless communication system 20 to facilitate progressive beamforming in which optimum beams are generated to correspond to the subarrays 32 and subsequently aggregated in a second optimization process that

20   corresponds to the array 22. The system 20 allows beamforming to be progressively completed in stages and is suitable for all modulation formats. Progressive beamforming of the system 20 substantially reduces computational complexity because it partitions the task into subtasks that each involve fewer elements. These concepts are further

25   detailed in the following descriptions of receive and transmit operations of the wireless communication system 20.

In a receive operation, each of the frequency converters 34 converts the frequency of data-carrying signals that correspond to its respective subarray 22 (of antennas 21). The data-carrying signals

30   are generally at a radio frequency in the subarrays 22 and at baseband or an intermediate frequency (IF) in the preprocessors 36, subarray beamformers 38 and the array beamformer 39.

Each subarray beamformer 38 receives the data-carrying signals of its respective subarray 32 and generates subarray signals

35   that correspond to a subarray beam using a defined set of

beamforming rules. Subsequently, the array beamformer receives these subarray signals and provides array signals that correspond to an array beam using a defined set of beamforming rules which need not be constrained to be the same rules used by the subarray

5   beamformers.

Thus, each subarray beamformer 38 is configured to process respective data-carrying signals to correspond to a receive subarray antenna beam of its respective subarray and the array beamformer 39 is configured to process respective data-carrying signals to

10   correspond to a receive array antenna beam of the array 22.

An exemplary beamforming rule multiplies signals derived from each antenna element by respective complex weights and adds the resulting products across the elements to form a sum signal. In general, the weights are optimized by maximizing or minimizing a

15   signal parameter or error function. In an exemplary embodiment, the difference between the sum and a known, predetermined signal is minimized.

The preprocessors 36 are preferably inserted between the frequency converters 34 and the subarray beamformers 38 to digitize

20   the data-carrying signals received from its respective frequency converter and to preprocess them to facilitate digital beamforming. Accordingly, the preprocessing are preferably configured to perform conventional processes which include automatic gain control (AGC), frequency correction, framing/time-of-arrival estimation, sampling

25   rate and time adjustment, channel correction, frequency domain transformation, downconversion, filtering, subsampling, direct sequence de-spreading and similar processes that are typically used to correctly capture the downconverted information in digital format.

The system 20 preferably includes the modem 30 which

30   demodulates the processed data-carrying signals from the array beamformer 39 to provide data at the system port 31. The modem may also provide an error correction function.

In a transmit operation of the system 20, data entering the system port 31 is modulated by the modem 30 and the modulated data

35   is passed to the array beamformer 39 which operates with a defined

set of beamforming rules to generate array signals which correspond to an array beam but comprise subarray signals that each correspond to a suboptimized beam of the array 22. Subsequently, the subarray beamformers 38 operate on the array signals from the array

5   beamformer with a defined set of beamforming rules to generate subarray signals which correspond to subarray beams of respective subarrays 32.

Thus, each subarray beamformer 38 is configured to process respective data-carrying signals to correspond to a transmit subarray

10   antenna beam of its respective subarray and the array beamformer 39 is configured to process respective data-carrying signals to correspond to a transmit array antenna beam of the array 22.

The transmit beamforming rules need not be constrained to be identical to those used in the receive operation described above. The

15   array and subarray beamformers typically use a predetermined set of complex weights, e.g., stored weights or weights derived from the receive operation described above.

The preprocessors 36 are preferably inserted between the frequency converters 34 and the subarray beamformers 38 to

20   transform the data-carrying signals wherein the transformation processes may include frequency translation, time domain transformation, upconversion, interpolation, frequency correction, direct sequence spreading, analog conversion, filtering or other similar processes suitable for transmitting the data-carrying signals.

25   The transformed signals are converted to RF signals in each of the frequency converters 34 and radiated from that converter's respective subarray 32.

The progressive beamforming of the invention substantially reduces the computational complexity of the communication system

30   20. If there were four subarrays 32 in the communication system, for example, the processing complexity required to invert matrices in the four subarray beamformers and the array beamformer would each correspond to the number 4^3 or 64. The processing complexity for all five beamformers would thus correspond to the number 5x64=324.

35   In contrast, the processing complexity required to invert

matrices in a conventional beamformer for all 16 antennas 23 would correspond to the number 16^3 or 4096 which is more than 12 times the complexity of the communication system of the invention. It is noted that the beamforming methods of the invention are especially suited to communication environments that are not excessively plagued with interference which would degrade the method results.

In different system embodiments, the frequency converters 34 can each be realized with a receiver 42, a transmitter 43 or a transceiver 44 as exemplified by an insertion arrow 46 in FIG. 1.

Attention is now directed to the wireless communication systems 60 and 70 of FIGS. 2A and 2B which are similar to the system 20 of FIG. 1 with like elements indicated by like reference numbers. In the systems 60 and 70, the frequency converter 24, preprocessor 26 and beamformer 28 perform operational functions similar to those described above for the partitioned frequency converters 34, preprocessors 36 and subarray and array beamformers 38 and 39 of FIG. 1.

The beamformer 28 of FIGS. 2A and 2B is coupled to exchange current data-carrying signals with the preprocessor 26 and the modem 30. In addition, the systems 60 and 70 include delays 62 and 72 positioned to provide at least one delay path for routing of the current data-carrying signals to thereby also provide delayed data-carrying signals to the beamformer. In particular, the data-carrying signals include symbols that have a symbol time duration and the delays 62 and 72 provide time delays that are selectable between a portion of a symbol time duration and a plurality of symbol time durations. The beamformer is thus enabled to process current and delayed data-carrying signals 64 and 66 to correspond to an antenna beam of the array 22.

The delay 62 is inserted between the preprocessor 26 and the beamformer 28 in FIG. 2A. Current data-carrying signals 64 can thus be exchanged between the preprocessor and the beamformer but these signals also pass through the delay 62 which provides delay paths so that delayed data-carrying signals 66 are also exchanged between the preprocessor and the beamformer. The delay 72 is coupled around the beamformer 28 in FIG. 2B. Current data-carrying signals 64 can thus

be exchanged between the preprocessor and the beamformer and between the modem and the beamformer but the beamformer has access to delayed data-carrying signals 66 that have already passed through the beamforming process.

5   The present invention recognizes that excessive multipath delay can generate inter-symbol interference between two adjacent symbols (e.g. in an orthogonal frequency division multiplexing (OFDM) system where multipath delay is longer than a guard interval). Accordingly, the wireless communication systems 60 and 70 are structured to

10   provide current and delayed versions of data-carrying signals so that the systems can optimize spatial information and also optimize information from non-coherent delays which are delays beyond the handling capability of the system modulation.

In particular, the data-carrying signals include symbols that

15   have a symbol time duration and the delays 62 and 72 provide time delays that are selectable between a portion of a symbol time duration and a plurality of symbol time durations. Although these time delays are envisioned to typically be one symbol in systems that use an OFDM or CDMA modulation format, they can, in general modulation

20   formats, be as long as a plurality of symbols. Information from each symbol delay is thus provided to thereby enhance the beamforming functions of the invention.

Attention is now directed to the wireless communication system 80 of FIG. 3 which is similar to the system 20 of FIG. 1 with

25   like elements indicated by like reference numbers. In the system 80, the frequency converter 24, preprocessor 26 and beamformer 28 perform operational functions similar to those described above for the partitioned frequency converters 34, preprocessors 36 and subarray and array beamformers 38 and 39 of FIG. 1.

30   In a receive operation of the system 80, data-carrying signals are received through the array 22, their frequency is altered in the signal converter 24 and they are transformed by the preprocessor 26 into transformed data-carrying signals.

For systems that utilize OFDM modulation formats, it is

35   recognized that the OFDM waveform contains a guard interval that

is inserted to eliminate inter-symbol interference caused by multipath signals, provided that the multipath delay is less than the size of the guard interval. For adaptive beamforming on OFDM waveforms, the present invention uses this guard interval and the inherent cyclic

5   nature of each OFDM symbol to minimize the computational requirements in processing all potentially useful multipath energy (i.e., all signals whose multipath delay is less than the guard interval).

In addition to transforming functions described above with

10   reference to the system 20 of FIG. 1, the preprocessor 26 of FIG. 3 is therefore configured to estimate the time-of-arrival or framing for the received data-carrying signals. As shown in FIG. 3, the time-of-arrivals 82 are provided to the beamformer 28 which is configured to process the transformed data-carrying signals to

15   correspond to a desired antenna beam of the array 22.

In particular, the beamformer 28 may modify the transformed data-carrying signals with complex weights and sum the products to form a weighted, summed signal which is compared to a desired, predetermined signal. A cost function represents the error between

20   the weighted, summed signal and the predetermined signal and the beamformer 28 is configured to minimize this cost function with appropriately-determined weights.

For example, the cost function can be minimized by calculating an NxN covariance matrix C in which each element C_{ij} is calculated

25   as the covariance of transformed signals i and j over a specified frame time (typically a frame time during the preamble of the data-carrying signals). Typically, an Nx1 vector D is also generated in which each element D_i is calculated as the correlation of a transformed signal i and the desired signal with a desired framing reference based on the

30   estimate time-of-arrival. An optimal set of complex weights is then computed by multiplying the inverse of matrix C by the vector D to realize an Nx1 vector K in which K_i is the optimized weight to multiply transformed signal i.

The invention notes that this approach produces an antenna

35   beam that is optimized for signals arriving at the array 22 coincident

with the estimated time-of-arrival used above to derive framing for the covariance functions. Accordingly, transformed signals with substantially different times-of-arrival will be rejected and their signal energy is unavailable to the resulting beam.

5   Although these signals can be included by recalculating a different beam for each possible estimated time-of-arrival, this substantially increases the computational effort (e.g., increases it by a factor equal to the number of estimated times-of-arrival considered). Processing each estimated time-of-arrival independently is also

10   sub-optimal because signals associated with different times-of-arrival are treated as interference (in calculation of the covariance matrix) and a portion of the beamforming benefit is therefore used in rejecting multipath energy that is associated with times-of-arrival that differ from the one being calculated.

15   As previously noted, OFDM systems include a guard interval which causes the OFDM frame of interest to be inherently cyclical. The invention recognizes that, with accurate framing of the OFDM frame, multipath energy which is within the guard interval will manifest itself as coherent energy in the calculation of the covariance matrix C. Therefore, all

20   multipath delays that are within the guard interval time can be accommodated with a single covariance matrix calculation.

        The calculation of multiple beams that are each associated with substantially different times-of-arrival of a multipath signal can therefore be accommodated (as long as the times of arrival are all

25   within the guard interval) with a single matrix inversion by expanding the covariance vector D into an NxN matrix. This matrix is composed of N vectors (each Nx1 in dimension) wherein D_{ij} is the covariance between a transformed version of the desired signal and the transformed data-carrying signals.

30   The transform to be applied to the desired signal is a phase shift across the tones of the desired OFDM waveform wherein the phase shift is based on the delays to be accommodated. The resulting set of weights is an NxN matrix W. Multiplying the 1xN input vector by the weight matrix W provides a 1xN vector that comprises the output of

35   each beam optimized for a different time-of-arrival. Optionally, these

beams can be equalized in the frequency domain (to make them phase coherent with each other). The resulting beams are then added to form a single beam. Alternatively, these beams may be maximally combined to minimize error or maximize a performance parameter.

5   Because the majority of computational requirements in conventional beamforming involves repeated inversions of the covariance matrix C for each delayed data-carrying signal, the calculation of a single inverted matrix represents a dramatic reduction in computational requirements. There is a performance

10   degradation associated with rejecting non-coherent multipath signals which are less than the guard interval and this degradation is minimized because a single covariance matrix is used to derive all beams.

Finally, equalization is improved because frequency domain

15   equalization is performed on beamformed signals with spatial processing gain and this enhances the performance of the equalization. This contrasts to conventional beamforming methods that perform equalization on a channel-by-channel basis which robs this process of the beamforming gain with the result that

20   beamforming accuracy is degraded.

Although various structures of the invention (e.g., preprocessor 26, and beamformer 28 of FIG. 1) are especially suited for realization with digital circuitry, they may also be realized with analog circuitry or combinations of digital and analog circuitry. The preprocessors,

25   beamformers and delays (62 and 72 in FIGS. 2A and 2B) can be realized, for example, with a) arrays of logic gates, b) an appropriately-programmed digital processor, or c) combinations of a) and b). The delays 62 and 72 of FIGS. 2A and 2B, for example, can be realized with various analog and digital delay circuits or processors.

30   The embodiments of the invention described herein are exemplary and numerous modifications, variations and rearrangements can be readily envisioned to achieve substantially equivalent results, all of which are intended to be embraced within the spirit and scope of the invention as defined in the appended

35   claims.